The speed of voluntary and priority-driven shifts of visual attention

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Word count: 8,741

Abstract

The question how fast spatial attention moves between different visual objects remains debated. We used electrophysiological measures to determine the speed of voluntary and visually guided shifts of attention. Participants shifted attention from a known benchmark object (T1) to a benchmark-defined target object (T2) in tasks where these shifts had to be controlled endogenously and tasks where they could be guided by visible stimulus attributes (target features or arrow cues). To track the speed of these attention shifts, we measured event-related potential (ERP) markers of attentional object selection (N2pc components). The N2pc to T1 emerged earlier than the N2pc to T2, confirming the presence of serial attention shifts. N2pc onset differences between T1 and T2 revealed that shifts guided by target features were triggered within 50 ms, whereas voluntary movements of attention took substantially longer (150 ms). Attention shifts signalled by arrow cues were initiated within about 100 ms. Results show that genuinely voluntary shifts of attention are slower than shifts that are guided by cues or target features, but can still be initiated more rapidly than has previously been assumed. They also demonstrate that EEG markers can track different types of serial attentional selection processes with high temporal precision.

Keywords: attention, cognitive control, event-related brain potentials, visual search

Public Significance Statement

How fast can observers shift their attention between different objects in the visual field? Using brain activity measures, we show that fully voluntary attention shifts can be triggered rapidly, within approximately 150 ms. However, attention shifts are even faster when they can be guided by the properties of visual objects.

Introduction

Serial and parallel selection models have been the focus of intense theoretical debates in the fields of visual attention and visual search. Serial models assume that attention is deployed sequentially to individual objects, and moves rapidly between different objects (Treisman & Gelade, 1980; Wolfe, 1994, 2007). Parallel models claim that attention can be allocated simultaneously to multiple objects but cannot be rapidly re-directed to new objects, resulting in long attentional dwell times (Duncan, Ward, & Shapiro, 1994; Ward, Duncan, & Shapiro, 1996). Because serial and parallel selection models differ fundamentally in their assumptions about the speed of attention shifts, a critical challenge for attention researchers is to measure this speed directly.

In many visual search tasks, the time required to find a target increases as a function of the number of display objects. Serial selection models interpret such search slopes as reflecting the speed with which attention moves between individual objects, which would yield shift times of approximately 50 ms per object (e.g., Wolfe, 1998). Because movements of attention during visual search are believed to be under voluntary control, doubts have been raised as to whether such voluntary shifts can really be initiated this rapidly (e.g., Desimone & Duncan, 1995). Endogenously controlled attention shifts are assumed to operate relatively slowly (e.g., Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989), and certainly not at the fast pace postulated by serial selection accounts. However, it is important to note that in most visual search tasks, shifts of attention between objects are not exclusively controlled by endogenous mechanisms, but are also driven by the visual properties of these objects. When target-defining features are known, observers activate an internal representation of these features ("attentional template"; Duncan & Humphreys, 1992), and attention shifts are determined by how well particular objects match the search template. Such template-guided attention shifts have been described as "priority-driven" (Horowitz, Wolfe, Alvarez, Cohen, & Kuzmova, 2009), because they are neither fully voluntary nor entirely stimulus-driven. It remains possible that priority-driven attentional movements are indeed as fast as assumed by serial selection models, whereas fully voluntary attention shifts operate at a slower pace.

Behavioural evidence for differences in the speed of voluntary and priority-driven attention shifts comes from a series of elegant experiments by Horowitz et al. (2009; see also Wolfe, Alvarez, & Horowitz, 2000). To study voluntary attention shifts, observers were instructed to monitor a rapid sequence of brief circular displays containing letters, and to shift their attention sequentially between adjacent locations within successive displays (e.g., clockwise from the top) to detect target objects. Because a target was present only in one display at one particular position (e.g., at 3 o'clock in the fourth display), it could only be found if attention was focused at this position at the correct point in time. Observers were able to perform this task only when each display was presented for at least 250 ms, suggesting that voluntary attention shifts operate relatively slowly. Similar results were obtained with static circular displays containing letters and mirror-reversed letters (Horowitz et al., 2009, Exp. 4). Here, a cue signalled the starting point for focal attention, and observers had to report the identity of the first mirror-reversed letter clockwise from the cue. Reaction times (RTs) increased as the number of objects between the cue and the target letter increased, with a slope of 200 ms per object. These findings suggest that fully voluntary shifts of attention operate at rates of about 200 – 250 ms per object. In contrast, the speed of priority-driven attention shifts was estimated to be 100 ms or even faster (Horowitz et al., 2009).

While these observations provide initial evidence for the speed differences between voluntary and priority-driven shifts of attention, it is difficult to draw firm conclusions about serial attentional selection processes on the basis of behavioural data alone (e.g., Townsend, 1990). To obtain more direct insights into the speed of voluntary and priority-driven attention shifts, additional on-line markers of attentional object selection are needed that can track such attention shifts continuously across time. In the current study, we employed the N2pc component of the event-related potential (ERP) to determine the speed with which attention moves between objects in the visual field. The N2pc is an enhanced negativity that is elicited at posterior electrodes contralateral to the visual field of a target object in multi-stimulus visual displays. This component typically emerges 180-200 ms after stimulus onset, is generated in extrastriate areas of the ventral visual processing stream (Hopf et al., 2000), and is believed to reflect the allocation of attention to candidate targets in visual search (e.g., Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 1999; see also Eimer, 2014, 2015, for further discussion). In many N2pc studies, displays only include a

single object with target-matching features. To assess the speed of serial attention shifts, search displays are needed that contain at least two candidate target objects. This presents a methodological challenge for N2pc-based research, because the N2pc reflects the difference between contralateral and ipsilateral ERP waveforms in response to laterally presented targets. When two targets appear on the same side, the corresponding N2pc components will overlap, and when they appear on opposite sides, N2pc components will cancel each other out. This problem can be overcome by presenting one of these targets on the vertical meridian (above or below fixation). Because vertical targets do not elicit N2pc components, the N2pc will exclusively reflect the selection of the horizontal target, independently of any additional attentional processing of the vertical target object (e.g., Eimer & Grubert, 2014; Eimer, Kiss, & Nicholas, 2011; Hickey, Di Lollo, & McDonald, 2009; Hickey, McDonald, & Theeuwes, 2006; Woodman, & Luck, 1999; Eimer & Grubert, 2014; Grubert & Eimer, 2015, 2016a; Jenkins, Grubert, & Eimer, 2016).

A second methodological challenge for investigating the speed of serial attention shifts is the necessity to ensure not only that participants move their attention sequentially between different target objects in the same display, but also that they select these objects in a constant order on each trial. Two previous N2pc studies have used different methods to encourage such constant serial selection strategies for priority-driven shifts of attention. Woodman & Luck (2003) presented search displays with two colour-defined target objects (Landolt squares) among multiple distractors. One target appeared close to fixation and the other at a more peripheral position (near versus far targets). On different trials, the near target appeared on the horizontal midline and the far target on the vertical midline, or vice versa. Participants had to report whether a gap in a specific position (e.g., at the top) was present in one of the two target objects. Woodman & Luck (2003) assumed that participants would consistently allocate attention first to the near target before shifting it to the far target. In line with this prediction, N2pc components to horizontal near targets preceded the N2pc to horizontal far targets by about 150 ms, suggesting that it took about 150 ms to move attention between the two target locations. A different method for imposing serial attention shifts was employed in a recent study from our lab (Grubert & Eimer, 2016b). Search displays contained four digits (two on the horizontal and two on the vertical midline). One vertical and one horizontal digit was coloured (targets) and the other two were grey (distractors). Critically, one target appeared in a known colour that remained constant

throughout the experiment (fixed-colour target), while the colour of the other target varied unpredictably across trials (variable-colour target). Participants were instructed to select the known fixed-colour target and to compare its value to the variable-colour target (e.g., "find the red digit and report whether the other coloured digit is bigger/smaller"). The N2pc to horizontal fixed-colour digits emerged 60 ms earlier than the N2pc to horizontal variable-colour digits, demonstrating that in this particular task, serial attention shifts were triggered even faster than in the study by Woodman & Luck (2003).

In these earlier N2pc studies of serial selection, target objects were defined by their colour. The attention shifts investigated in these studies were therefore priority-driven, because they could be controlled by colour-specific search templates. In contrast, the speed of fully voluntary shifts of attention has never been investigated with electrophysiological measures. Do attention movements that are under full voluntary control operate more slowly than priority-driven attention shifts, as suggested by previous behavioural evidence (Horowitz et al., 2009)? One goal of the two experiments reported here was to answer this question. Another goal was to compare the speed of priority-driven attention shifts when these shifts are controlled by different types of priority signals (spatial cues versus target features).

In both experiments, search displays contained four alphanumerical objects (two on the horizontal and two on the vertical midline; see Figure 1). One of them was the response-relevant target, and participants' task was to report its category (letter versus digit). Critically, which object was the target on any given trial was not known in advance, because this was determined by another object in the same display (the "benchmark"). Participants therefore had to first process this benchmark object (T1) before they could shift attention to the response-relevant target (T2). The benchmark object was defined by a known constant feature (shape in Experiment 1, colour in Experiment 2), to ensure that attention shifts to this object could be triggered rapidly and consistently in all trials. In Experiment 1, the benchmark location was signalled by a unique shape (e.g., the only circle among three squares; Figure 1). There were two task conditions. In the priority-driven shift task, the response-relevant T2 was the object that matched the colour of the object at the benchmark location (e.g., "find the object within the circle and report the category of the other object in the same colour"). Here, attention shifts from T1 to T2 were priority-driven because they were determined by a colour match between T1 and T2. In the voluntary shift

task, participants had to localize the T1 benchmark shape, and then move their attention in a pre-specified direction (either clockwise or anticlockwise relative to the benchmark, varied across blocks) towards the response-relevant T2 object (e.g., "report the category of the object that is located clockwise from the circle"). Here, attention shifts between T1 and T2 had to be initiated in a fully voluntary (endogenous) fashion, because there were no visual features associated with the status of T2 as the target object. In both tasks, T1 appeared on the horizontal midline and T2 on the vertical midline on 50% of all trials and vice versa on the other trials, so that N2pc components could be measured separately and independently to T1 and T2. Because the T1 benchmark had to be processed in order to determine the response-relevant T2 object in both tasks, N2pc components to horizontal T1 objects should always precede N2pc components to horizontal T2 objects, reflecting serial attention shifts to T1 and then from T1 to T2. Critically, the onset delay between these two N2pc components should reflect the time required for attention to shift between T1 and T2. If fully voluntary shifts of attention are slower than priority-driven shifts (Horowitz et al., 2009), this should be reflected by longer T1/T2 N2pc onset latency differences in the voluntary shift task of Experiment 1.

Experiment 1

Materials and Methods

Participants

Fifteen participants were paid to take part in Experiment 1. Two participants were excluded from analysis due to low accuracy (with error rates higher than 30%), and another participant was excluded due to excessive eye movement activity (resulting in a loss of more than 50% of all data during artefact rejection). The remaining twelve participants were aged between 20 and 41 years (*M* = 29, *SD* = 5.92). Six were female and three were left-handed. All participants had normal or corrected-to-normal vision. To ensure a large enough sample size providing enough power to reliably exclude false rejection of the null hypothesis, power (1-β) was tested with the G*Power program (Faul, Erdfelder, Lang, & Buchner, 2007), using the a priori option and the η_p^2 effect size (.87) of Experiment 3 in Grubert & Eimer

(2016b; n=12). Power analysis revealed a test power of .995 (with an effect size *f* determined according to Cohen, 1988, of 2.59) and suggested that a sample size of n=6 was sufficient to achieve the desired effect size of .87. The study was conducted in accordance with the Declaration of Helsinki, and was approved by the Psychology Ethics Committee, Birkbeck, University of London.

Stimuli and Procedure

Stimuli were presented on a 22-inch Samsung wide SyncMaster 2233 LCD monitor (resolution of 1280x1024 pixels, 100 Hz refresh rate; 16ms black-to-white-to-black response time, as verified with a photodiode). Participants were seated in a dimly illuminated cabin. The monitor was placed at a viewing distance of approximately 100 cm. Stimulus presentation, timing, and response collection were controlled by a LG Pentium PC running under Windows XP, using the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.).

Stimuli were coloured uppercase letters (A, D, E, K, N, or U) or digits (2, 4, 5, 6, 7, or 9), each covering 0.5° x 0.5° of visual angle. They were surrounded by grey (CIE xyY colour coordinates: .321/.352) outline shapes (circles or squares; 0.2° line width), subtending 1.1° x 1.1° of visual angle. All stimuli were presented at an eccentricity of 3.0° from central fixation (with respect to the centre of the letters/digits) against a black background. The four possible object colours were red (.623/.337), green (.266/.564), blue (.194/.214) and magenta (.307/.180). All colours were equiluminant (~7.6 cd/m^2). A central grey fixation point (0.2° x 0.2°) remained continuously present throughout each experimental block. Each stimulus display contained four objects, of which two shared one colour and two shared another colour. Both colours were selected randomly from the four possible colours on each trial. One of these four objects was surrounded by the benchmark shape (e.g., circle), and the three other objects were each surrounded by the other shape (e.g., square; Figure 1, top panel). Circles served as benchmark shape for six participants, and squares were the benchmark shape for the other six participants. This benchmark shape remained constant for each participant throughout the experiment. On each trial, four different stimulus identities were selected randomly from the twelve-item set of letters and digits. Stimulus displays were presented for 100 ms and the interval between the offset of the stimulus display in one trial and the onset of the stimulus display in the next trial was 1900 ms.

Two task conditions were tested in Experiment 1. In both tasks, the known shape marked the benchmark location (first target; T1). In the priority-driven shift task, participants had to report the alphanumerical category (letter or digit) of the item (second target; T2) that matched the colour of the object at the benchmark location (i.e., a digit "7" with respect to the red benchmark target T1 in Figure 1, top panel). In the voluntary shift task, observers had to report the alphanumerical category of the item that was one position clockwise or anticlockwise from the benchmark location (i.e., a letter "A" which is located anti-clockwise relative to the red benchmark object in Figure 1, top panel). Shift direction (clockwise or anticlockwise) remained constant within each block, but alternated across experimental blocks. At the beginning of each block, participants were presented with an on-screen specification of the required shift direction for this block. On 50% of trials, T1 was presented on the horizontal midline (to the left or right of fixation), and T2 was presented on the vertical meridian (above or below fixation). On the other 50% of trials, T1 appeared on the vertical and T2 on the horizontal meridian. Trials where T2 was a letter or digit were equiprobable and randomly intermixed in each block. Responses were given by pressing one of two purpose-built vertically aligned response keys. The response-to-key mapping, as well as the hand-to-key mapping, was counterbalanced across participants.

Experiment 1 contained 24 blocks, with 32 trials per block. Each condition was run in 12 successive blocks, and was preceded by two practice blocks. In the priority-driven shift task, each block contained four trials for each combination of horizontal target [T1 horizontal, or T2 horizontal], position of horizontal target [left, or right] and position of vertical target [top, or bottom]. In the voluntary shift task, each block contained 8 trials for each combination of T1 position [left, right, top, or bottom]. The position of T2 relative to T1 [clockwise, or anticlockwise] was alternated block-wise, and the initial direction in the first block was counterbalanced across participants.

EEG Recording and Data Analyses

The continuous EEG was DC-recorded from 27 scalp electrodes at standard positions of the extended 10/20 system. EEG data were sampled at a rate of 500 Hz, with a digital low-pass filter of 40 Hz. No other offline filters were employed. All electrode impedances were kept below 5 kΩ. During recording, all channels were referenced to the left earlobe. They were then re-referenced offline to the average of both earlobes. Trials containing eye

movement artefacts (horizontal eye movements associated with EEG activity exceeding ±30 μV in the HEOG channels; eye blinks associated with signals exceeding ±60 μV at Fpz), artefacts due to muscular movements (activity exceeding ±80 μV in any other channel), and trials with incorrect, anticipatory (faster than 200 ms), very slow (slower than 1800 ms), or missing responses were excluded from EEG analyses. After excluding trials based on these criteria, the rate of trials that were retained for analyses was 83.1% (ranging from 70.5% to 93.5% between participants) in the priority-driven shift task, and 85.7% (ranging from 70.0% to 94.5% between participants) in the voluntary shift task. EEG was segmented into epochs from 100 ms prior to 500 ms after the onset of each stimulus display, relative to a 100 ms pre-stimulus baseline. EEG was averaged separately for each of the eight combinations of shift task (priority-driven or voluntary), horizontal target (T1 or T2) and location of the horizontal target (left or right).

N2pc components were quantified on the basis of ERPs measured at lateral posterior electrodes PO7 and PO8. N2pc onset latencies were determined on the basis of difference waveforms (computed by subtracting ipsilateral from contralateral ERPs at PO7 and PO8) with a jackknife-based procedure (Miller, Patterson, & Ulrich, 1998; Ulrich & Miller, 2001). Twelve grand-average difference waves were computed for each task condition, with each difference wave excluding one different participant from the original sample. N2pc onset was defined as the point in time when a difference wave fell below a fixed onset criterion of -0.5μV (starting at the maximum negative peak of each difference waveform and moving backwards in time). N2pc onset latency differences between trials with horizontal T1 and T2 objects were assessed with repeated-measures ANOVAs and paired *t*-tests. All *F*- and *t*-values were corrected according to the formulas described by Ulrich and Miller (2001) and Miller et al. (1998), respectively. The corrected statistical values are indicated with F_c and t_c, respectively. All *t*-tests were two-tailed and Bonferroni-corrected where necessary. To confirm that N2pc components were reliably elicited both for T1 and T2 objects in both tasks, N2pc mean amplitudes measured at electrodes PO7/PO8 contralateral and ipsilateral to these objects were compared with two-tailed paired *t*-tests. These mean amplitudes were obtained within 100 ms time windows starting at the onset latency of the respective N2pc component, rounded to the nearest 10 ms. For T1 objects, these time windows were 210-310 ms and 230-330 ms post-stimulus in the priority-driven and voluntary shift tasks,

respectively. For T2 objects, the corresponding latency windows were 260-360 ms and 350-450 ms, respectively.

To measure effect sizes, Cohen's *d* (Cohen, 1988) was computed for all *t*-tests, and partial eta-squared (labelled η_p^2) was determined for all ANOVAs. To correct individual group means and standard deviations of jackknifed samples, the jackknifed group means of N2pc latency values were fed into repeated-measures ANOVAs where the error variance was corrected according to the formula described by Ulrich and Miller (2001). Effect sizes for N2pc latency measures are therefore reported as $\eta_p^2{}_c$.

Results

Behavioural Performance

Anticipatory or exceedingly slow RTs (faster than 200 ms or slower than 1800 ms) were removed from analysis, resulting in the exclusion of less than 0.9% of all trials. A repeated-measures ANOVA with the factors Task (priority-driven shift, voluntary shift) and Display Type (T1 horizontal/T2 vertical versus T1 vertical/T2 horizontal) revealed a main effect of Task on RTs on trials with correct responses, $F(1,11) = 6.28$, $p < .05$, $\eta_p^2 = .36$, as RTs in the priority-driven shift task were slower than in the voluntary shift task (987 ms versus 943 ms). There was no main effect of Display Type and no interaction between Task and Display Type, both $F(1,11) < .61$, $p > .450$, $\eta_p^2 < .06$. For error rates, there was also a main effect of Task, $F(1,11) = 13.33$, $p < .01$, $\eta_p^2 = .55$, with higher error rates in the priority-driven shift task condition relative to the voluntary shift task (8.2% versus 6.3%), but no main effect of Display Type, $F(1,11) = 1.21$, $p = .295$, $\eta_p^2 = .10$, and no significant interaction between Task and Display Type, $F(1,11) = 3.91$, $p = .074$, $\eta_p^2 = .26$.

In both tasks, the alphanumerical category of T1 and T2 was the same (both letters or both digits) on half of all trials (congruent trials) and different on the other half (incongruent trials). To assess congruency effects on RTs, a repeated-measures ANOVA was conducted with the factors Task and Congruency (congruent, incongruent). A main effect of Congruency was obtained, $F(1,11) = 8.04$, $p < .05$, $\eta_p^2 = .42$, reflecting faster RTs on congruent relative to incongruent trials (953 ms versus 976 ms). There was no interaction

between Congruency and Task, $F(1,11) = 0.11$, $p = .747$, $\eta_p^2 = .01$, indicating that similar congruency effects were present in the priority-driven and voluntary shift tasks.[1]

N2pc Components

Figure 2 (left and middle panels) shows ERPs at posterior electrodes PO7/PO8 contralateral and ipsilateral to the side of a horizontal benchmark object (T1) and a horizontal response-relevant object (T2), separately for the priority-driven shift task (top panels) and the voluntary shift task (bottom panels). The right panels of Figure 2 show N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for horizontal T1 and T2 objects and both tasks. Solid N2pc components were elicited in response to both types of targets in both tasks. Importantly, the N2pc to T2 was delayed relative to the N2pc to T1, indicating that the benchmark object was indeed selected first, before attention was shifted to the response-relevant T2 object. The critical finding was that this T1/T2 N2pc onset difference was substantially longer in the voluntary shift task than in the priority-driven shift task.

These observations were confirmed by analyses of N2pc onset latencies and mean amplitudes. A repeated-measures ANOVA on N2pc onset latencies with the factors Task and Display Type (T1 horizontal versus T2 horizontal) revealed a main effect of Display Type, $F_c(1,11) = 22.93$, $p < .001$, $\eta_p^2{}_c = .68$, confirming that the N2pc to horizontal T2 objects was delayed relative to the N2pc to horizontal T1 objects. Additionally, an interaction between Task and Display Type was observed, $F_c(1,11) = 8.14$, $p < .05$, $\eta_p^2{}_c = .43$, reflecting the fact that this T1/T2 N2pc delay was larger in the voluntary shift task. Follow-up *t*-tests comparing N2pc onset latencies in response to T1 and T2 revealed that in the priority-driven shift task,

[1] Because T2 was defined as the object that shared the colour of T1 in the priority-driven shift task, attention shifts in this task were always between two objects in the same colour. In the voluntary shift task, where T2 was defined by its clockwise/counterclockwise position relative to T1, attention shifts were equally likely to be required between same-colour and different-colour T1 and T2 objects. A paired *t*-test revealed that RTs on same-colour shift trials were faster than on different-colour shift trials in this task (930 ms versus 956 ms; $t(11) = 2.66$, $p < .05$, $d = .14$).

the N2pc to horizontal T2 objects was delayed by 47 ms relative to the N2pc to horizontal T1 objects (259 ms versus 212 ms; $t_c(11) = 2.30$, $p < .05$, $\eta_p^2{}_c = .33$). In the voluntary shift task, this T1/T2 N2pc onset difference was 128 ms (354 ms versus 227 ms; $t_c(11) = 5.07$, $p < .001$, $\eta_p^2{}_c = .69$). When N2pc onset latencies were compared across both tasks, no significant difference was found for horizontal T1 objects, $t_c(11) = .59$, $p = .565$, $\eta_p^2{}_c = .03$, while the N2pc to horizontal T2 objects emerged reliably later in the voluntary shift task as compared to the priority-driven shift task (354 ms versus 259 ms; $t_c(11) = 7.18$, $p < .001$, $\eta_p^2{}_c = .82$).

To confirm that N2pc components were reliably elicited by horizontal T1 and T2 objects in both tasks, a repeated-measures ANOVA of N2pc mean amplitudes (obtained within different post-stimulus latencies for T1 and T2 objects; see Methods section) was run with the factors Task, Display Type and Laterality (electrode contralateral, versus ipsilateral to the side of the horizontal target). A main effect of Laterality, $F(1,11) = 22.12$, $p < .001$, $\eta_p^2 = .67$, confirmed that N2pc components were reliably elicited by horizontal target items. There was no interaction between Task and Laterality, $F(1,11) = .03$, $p = .863$, $\eta_p^2 = 0$, showing that N2pc components of similar size were elicited in both tasks. An interaction between Display Type and Laterality, $F(1,11) = 7.01$, $p < .05$, $\eta_p^2 = .39$, was due to the fact that N2pc components to T1 benchmark objects were generally larger than N2pcs to response-relevant T2 objects (see Figure 2). There was no three-way interaction between Task, Display Type, and Laterality, $F(1,11) = .07$, $p = .793$, $\eta_p^2 = 0$.

Discussion of Experiment 1

The N2pc results of Experiment 1 were in line with previous suggestions based on behavioural results that purely voluntary attention shifts are slower than priority-driven shifts (Horowitz et al., 2009). Reliable N2pc components were elicited both in response to lateral benchmark items (T1) as well as to lateral response-relevant targets (T2). The N2pc to T1 objects preceded the N2pc triggered by T2 objects in both shift tasks. This demonstrates that participants first attended to the benchmark before shifting attention to the response-relevant T2 objects, both when these objects were indicated by the colour of the benchmark (priority-driven shifts) or its location (clockwise or anticlockwise voluntary shifts). Critically, the onset difference between N2pc components to T1 and T2 objects was larger in the voluntary shift task (128 ms) than in the priority-driven shift task (47 ms). The

rapid speed of priority-driven shifts of attention indicated by the N2pc results of Experiment 1 is consistent with the findings of an earlier study (Grubert & Eimer, 2016b) that found N2pc onset latency differences of about 60 ms between a known fixed-colour target and an unpredictable variable-colour target. Critically, the speed of fully voluntary attention shifts was tracked for the first time with ERP markers in Experiment 1. The observation that the N2pc to T2 objects emerged 128 ms later than the N2pc to T1 benchmark objects in the voluntary shift task suggests that although fully endogenous attention shifts that cannot be guided by visual signals are slower than priority-driven shifts, they are still elicited relatively rapidly, and faster than suggested by the behavioural results reported by Horowitz et al. (2009). To test the possibility that the slower shift times in the voluntary as compared to the priority-driven shift task were caused by the fact that participants had to change shift direction from clockwise to anticlockwise and back across successive blocks in the voluntary task, we ran an additional N2pc analysis for this task, excluding the first six trials from each block. The temporal pattern of N2pc components was virtually identical to the pattern observed when all trials were included, which makes it unlikely that the requirement to change shift direction in each block was responsible for the delayed shift speed in the voluntary task.

There was one puzzling inconsistency between the behavioural and N2pc results observed in Experiment 1. While the temporal pattern of N2pc components demonstrated faster attention shifts towards response-relevant T2 objects in the priority-driven shift task, target RTs were faster in the voluntary task. This RT delay in the priority-driven shift task may have been due to the fact that while T2 objects were defined by their colour, response selection was based on the shape-related categorization of these objects as letters or digits. This need to shift from colour to shape processing may have slowed response selection in the priority-driven task relative to the voluntary task, where T2 objects were defined by their spatial relationship to the benchmark shape, and no shift between relevant feature dimensions was needed. One goal of Experiment 2 was to assess this hypothesis.

Experiment 2

In the priority-driven shift task of Experiment 1, movements of attention were guided by the presence of a benchmark-matching colour at the target location of an

attention shift. In this case, priority-driven attention was “pulled” by a particular target-defining feature. There is another type of priority-driven attention where target locations for an attention shift are defined by visual signals at a different location, such as spatially informative cues. In this case, attention is “pushed” towards a new location by the visual properties of a cue at a currently attended position. A classic example is the spatial cueing paradigm developed by Posner and colleagues (e.g., Posner, Snyder, & Davidson, 1980; Posner, 1980), where informative arrow cues signal the location where expected target objects are likely to appear. Behavioural studies have suggested that attention shifts triggered by arrow cues are relatively slow, and take about 250-300 ms to be completed (e.g., Müller & Rabbitt, 1989; Cheal & Lyon, 1991; see also Müller, Teder-Sälejärvi, & Hillyard, 1998, for electrophysiological evidence). Although such cued attention shifts are usually described as “endogenous”, they are controlled by visual attributes of the cue (e.g., arrow direction). For this reason, and analogous to template-guided shifts of attention, attention shifts in response to spatial cues are also priority-driven. The aim of Experiment 2 was to employ N2pc components to determine the speed of such priority-driven shifts of attention that are triggered by spatial cues, and to compare it to the speed of fully voluntary attention shifts. Procedures were similar to Experiment 1. T1 benchmark objects were now defined by colour, and there were two shift tasks (see Figure 1). In the priority-driven task, the response-relevant T2 object was signalled by the arrow cue at the benchmark location. In the voluntary task, T2 was the object that was located clockwise or anticlockwise relative to the colour-defined benchmark.

Materials and Methods

Participants

Thirteen participants were paid to take part in Experiment 2. One participant was excluded from analysis due to excessive eye movement activity (leading to a loss of more than 50% of all trials during artefact rejection). The remaining twelve participants were aged between 24 and 42 years (M = 31, SD = 5.37). Five were female and three were left-handed. All participants had normal or corrected-to-normal vision.

Stimuli and Procedure

These were analogous to Experiment 1 with the following exception. The four alphanumerical objects in each display now appeared in four different colours (red, green, magenta and blue, Figure 1, middle and bottom panels). Colour coordinates and luminance were the same as in Experiment 1. Displays again contained one benchmark object (T1), one second response-relevant object (T2), and two nontargets. One of these target objects always appeared on the vertical meridian and one on the horizontal meridian, as in Experiment 1. Importantly, T1 was now defined by its colour, which remained constant for each participant, and was counterbalanced across participants (each of the four colours defined the benchmark object for three participants). Two task conditions were tested. In the priority-driven shift task, each of the four letters or digits (0.5° x 0.5°) was surrounded by matching-colour outline arrow shapes (0.2° line width; sized 1.1° x 1.1° of visual angle, Figure 1, middle panel). Each arrow was tilted by 45° with respect to the horizontal so that it pointed to one of its two adjacent objects (e.g., the arrow surrounding the right-sided stimulus would either point to the top or bottom stimulus; see Figure 1, middle panel). Participants' task was to locate the arrow in the benchmark colour (T1), and then to direct attention to the object (T2) specified by the direction of this arrow and report its alphanumerical category (e.g., the letter "K" signalled by the red benchmark arrow in Figure 1). In the voluntary shift task, the four letters and digits were presented without arrow shapes. Observers had to localize the coloured benchmark object (T1) and to report the category of the object (T2) at the clockwise or anticlockwise location relative to this object (e.g., the letter "A", located clockwise relative to the red benchmark object, in Figure 1, bottom panel). All other methodological and procedural aspects of the stimulus presentation, response collection and trial balancing were identical to Experiment 1.

EEG Recording and Data Analyses

All aspects of EEG recording and data analyses were identical to Experiment 1. After artefact rejection and exclusion of anticipatory, slow, or incorrect responses, the proportion of retained trials was 85.7% (ranging from 71.6% to 96.9% between participants) in the priority-driven shift task, and 85.6% (ranging from 70.6% to 96.8% between participants) in the voluntary shift task. N2pc mean amplitudes were measured within the 100 ms time window starting at the onset latency of the respective wave form. The time windows for the

N2pc mean amplitude analyses (defined again as the 100 ms time window following N2pc onset for a particular trial condition) were 180-280 ms and 190-290 ms post-stimulus for horizontal T1 trials in the priority-driven and voluntary shift tasks, respectively. For horizontal T2 trials, the respective time windows were 290-390 ms and 360-460 ms.

Results

Behavioural Performance

Anticipatory or exceedingly slow RTs (faster than 200 ms or slower than 1800 ms) were removed from analysis, resulting in the exclusion of less than 0.5% of all trials. A repeated-measures ANOVA with the factors Task (priority-driven versus voluntary shift) and Display Type (T1 horizontal, T2 horizontal) revealed a main effect of Task on RTs on trials with correct responses, $F(1,11) = 12.73$, $p < .01$ $\eta_p^2 = .54$, with faster RTs in the priority-driven relative to the voluntary shift task (863 ms versus 910 ms). There was no main effect of Display Type, $F(1,11) = 2.61$, $p = .192$, $\eta_p^2 = .19$, and no interaction between Task and Display Type, $F(1,11) = 1.24$, $p = .290$, $\eta_p^2 = .10$. For error rates, there was no significant difference between the priority-driven and voluntary shift tasks (8.2% versus 7.1%; $F(1,11) = 3.36$, $p = .094$, $\eta_p^2 = .23$), no main effect of Display Type, and no interaction between Task and Display Type, both $F(1,11) < .17$, $p > .694$, $\eta_p^2 < .02$.

As in Experiment 1, the assessment of T1-T2 congruency effects on RTs revealed a main effect of Congruency, $F(1,11) = 19.85$, $p < .001$, $\eta_p^2 = .64$, with faster RTs on congruent relative to incongruent trials (845 ms versus 886 ms). There was again no interaction between Task and Congruency, $F(1,11) = .08$, $p = .782$, $\eta_p^2 = .01$.

N2pc Components

Figure 3 shows ERPs at posterior electrodes PO7/PO8 contralateral and ipsilateral to the side of horizontal benchmark T1 objects and horizontal response-relevant T2 objects in the priority-driven and voluntary shift tasks, together with the corresponding contralateral-ipsilateral N2pc difference waveforms. As in Experiment 1, the N2pc to T1 objects emerged earlier than the N2pc to T2 objects, and this T1/T2 N2pc latency difference was larger in the voluntary shift task.

A repeated-measures ANOVA on N2pc onset latencies with the factors Task and Display Type (horizontal T1 versus horizontal T2) revealed a main effect of Display Type, $F_c(1,11) = 1605.02$, $p < .001$, $\eta_p^2{}_c = .99$, confirming that N2pc components to horizontal T2 objects emerged later than N2pcs to horizontal T1 objects. A significant Task x Display Type interaction, $F_c(1,11) = 24.02$, $p < .001$, $\eta_p^2{}_c = .69$, showed that this T1/T2 delay was more pronounced in the voluntary shift task. For the priority-driven shift task with arrow cues, the N2pc to horizontal T2 objects was delayed by 106 ms relative to the N2pc to horizontal T1 benchmark objects (289 ms versus 183 ms; $t_c(11) = 15.98$, $p < .001$, $\eta_p^2{}_c = .96$). For the voluntary shift task, this delay was 163 ms (356 ms versus 194 ms; $t_c(11) = 24.27$, $p < .001$, $\eta_p^2{}_c = .98$). As in Experiment 1, the N2pc to horizontal T1 benchmark objects did not differ reliably between the two tasks, $t_c(11) = 1.76$, $p = .105$, $\eta_p^2{}_c = .22$. In contrast, the N2pc to horizontal T2 objects emerged significantly later in the voluntary shift task relative to the priority-driven shift task (356 ms versus 289 ms; $t_c(11) = 6.72$, $p < .001$, $\eta_p^2{}_c = .80$).

The analysis of N2pc mean amplitudes with the factors Task, Display Type and Laterality (electrode contralateral versus ipsilateral to the side of the horizontal target) confirmed the presence of reliable N2pc components in Experiment 2 (main effect of Laterality: $F(1,11) = 95.25$, $p < .001$, $\eta_p^2 = .90$). There was no interaction between Task and Laterality, $F(1,11) = .87$, $p = .372$, $\eta_p^2 = .07$, and also no Display Type x Laterality interaction, $F(1,11) = 1.29$, $p = .28$, $\eta_p^2 = .10$, indicating that N2pc amplitudes were not reliably different for horizontal benchmark (T1) and response-relevant (T2) targets.

Analyses of N2pc Onset Latencies across Experiments 1 and 2

To obtain further insights into speed differences between fully voluntary attention shifts and different types of priority-driven shifts, additional N2pc latency analyses were conducted across the two experiments. For the N2pc to horizontal benchmark objects (T1), a 2-way mixed-design ANOVA with the within-subjects factor Task (priority-driven versus voluntary shift) and the between-subjects factor Selection Attribute (shape in Experiment 1 versus colour in Experiment 2) obtained no main effect of Task, $F_c(1,22) = 1.02$, $p = .496$, $\eta_p^2{}_c = .04$, confirming that the speed with which attention was allocated to the benchmark item did not differ between priority-driven and voluntary shift tasks. The effect of Selection Attribute approached significance, $F_c(1,22) = 3.34$, $p = .081$, $\eta_p^2{}_c = .13$, as N2pcs to colour-

defined benchmark objects in Experiment 2 tended to emerge earlier than N2pc components to the shape-defined benchmark objects in Experiment 1 (196 ms versus 219 ms). For the N2pc to T2 objects, there were no onset latency differences between the voluntary shift tasks of Experiments 1 and 2, $F_c(1,22) = .02$, $p = .894$, $\eta_p^2 = 0$. However, there was a difference in N2pc onset latencies to T2 objects between the two types of priority-driven attention shifts examined in Experiments 1 and 2. When the location of T2 was signalled by its colour match with the benchmark object (Experiment 1), the N2pc emerged earlier than when it was indicated by an arrow at the benchmark location (Experiment 2; 259 ms versus 289 ms; $F_c(1,22) = 14.16$, $p < .01$, $\eta_p^2{}_c = .39$). To confirm that priority-driven shifts of attention were faster when they were controlled by target colour than by arrow cues, N2pc onset latencies to horizontal T1 objects were subtracted from onset latencies to T2 objects, and the resulting difference values were compared across these two types of priority-driven selection tasks. Shift times were indeed reliably faster for the colour-guided shifts in Experiment 1 relative to the arrow-guided shifts in Experiment 2 (47 ms versus 106 ms), $F_c(1,22) = 7.64$, $p < .05$, $\eta_p^2{}_c = .26$.). An analogous comparison between the two voluntary shift tasks of Experiments 1 and 2 found that shift times were not significantly different (128 ms versus 163 ms; $F_c(1,22) = 1.74$, $p = .200$, $\eta_p^2{}_c = .07$).

Discussion of Experiment 2

The results of Experiment 2 demonstrate that priority-driven shifts are faster than fully voluntary shifts of attention even when priority-driven attention is not “pulled” towards target-matching features, as in Experiment 1, but is “pushed” towards target locations signalled by spatial cues. In the voluntary shift task, the N2pc to T2 objects was delayed by 163 ms relative to the onset of N2pc components triggered by T1 objects. This T1/T2 N2pc onset difference did not differ reliably from the (numerically smaller) difference observed in the voluntary shift task of Experiment 1. Together, these results strongly suggest that fully voluntary shifts of attention between visual objects can be elicited within less than 200 ms. For priority-driven shifts triggered by arrow cues, the N2pc to T2 targets emerged 106 ms later than the N2pc to the T1 benchmark cues. This shows that cued shifts of attention are triggered faster than fully voluntary attention shifts, and also more rapidly than was suggested by previous behavioural studies (e.g., Cheal & Lyon, 1991). On the other

hand, these cue-triggered attention shifts appear to operate at a slower pace than the feature-guided shifts investigated in Experiment 1.

While target RTs were unexpectedly faster in the voluntary task relative to the priority-driven shift task in Experiment 1, RTs were faster in the priority-driven task of Experiment 2, consistent with the N2pc evidence for more rapid attention shifts in this task. This supports the hypothesis that the RT costs found for the priority-driven task in Experiment 1 was due to the fact that different dimensions (colour versus shape) were relevant to find T2 and to select the correct response. No such shift between selection criteria was required in the priority-driven task of Experiment 2, where T2 was signalled by the shape of the benchmark arrow.

General Discussion

The goal of the current study was to measure the speed of serial attention shifts between visual objects, and to find out whether fully voluntary shifts of attention are slower than priority-driven shifts that can be guided by visual features. We employed a novel task design where observers first had to localise and/or identify a benchmark (T1) object, in order to determine which other object in the search display (T2) was the response-relevant target. N2pc components in response to T1 objects preceded N2pc components to T2 objects in all task conditions. This shows that as intended, attention was first directed to T1 before a second attention shift towards T2 was initiated. Critically, the onset latency difference between these two N2pc components could therefore be used to determine the speed of these serial attention shifts from T1 to T2.

In the voluntary shift tasks of Experiments 1 or 2, the benchmark object (T1) was defined by its shape or its colour, and participants had to move their attention either clockwise or anticlockwise from the benchmark to another response-relevant object (T2). In these tasks, the initial allocation of attention to T1 objects was priority-driven, as it was guided by the known shape or colour of the benchmark object. In contrast, because the location of T2 was not signalled by any visual features in the search displays, shifts of attention from T1 to T2 had to be exclusively based on endogenous (voluntary) control processes. The N2pc to T2 objects emerged 128 ms (Experiment 1) and 163 ms (Experiment

2) later than the N2pc to T1 objects in these voluntary shift tasks. These findings provide new objective estimates for the speed of fully voluntary attention movements. The shift times suggested by this temporal pattern of N2pc components are faster than the shift rates of 200 – 250 ms per object that were inferred by Horowitz et al. (2009) on the basis of behavioural measures. This discrepancy may be primarily due to differences in attentional task demands. In the experiments by Horowitz et al. (2009), participants had to execute multiple serial attention shifts on each trial, and each attended object had to be identified as target or nontarget before attention could move to the next location. In the voluntary shift tasks of the present study, only one voluntary movement of attention (from T1 to T2) was required, and the T1 benchmark item had to be localised, but not fully identified. Even though the identity of T1 was irrelevant, there were still behavioural congruency effects in these voluntary shift tasks (i.e., faster RTs on trials where the alphanumerical category of T2 items matched the category of the object at the benchmark location), suggesting that the category of T1 benchmark objects was in fact discriminated. The size of these congruency effects did not differ between the voluntary and priority-driven shift tasks, which further suggests that T1 category was processed in a task-independent automatic fashion (see also Egeth, Jonides, & Wall, 1972; Duncan, 1980, for similar conclusions). Overall, the N2pc results obtained in the voluntary shift tasks provide novel electrophysiological insights into the pace of fully voluntary shifts of attention. They show that the "clock speed of free will" (Horowitz et al., 2009) in the control of spatial attention can be measured objectively. Voluntary shift of attention from a currently attended location to a new object can be initiated within approximately 150 ms.

The other main finding from the present study was that priority-driven shifts of attention are faster than purely voluntary shifts, confirming previous suggestions based on behavioural results (Horowitz et al., 2009). In the priority-driven shift task of Experiment 1, where T2 matched the colour of the object at the T1 benchmark location, the T1/T2 N2pc onset latency difference was 47 ms. The fast pace of colour-guided shifts observed in Experiment 1 is also consistent with a the results of our recent N2pc study (Grubert & Eimer, 2016b), where the N2pc elicited by known fixed-colour target preceded the N2pc to a variable-colour target by 60 ms. It is notable that in an earlier N2pc investigation of colour-guided serial attention shifts (Woodman & Luck, 2003), considerably longer shift times (100 – 150 ms) were observed. In this study, a difficult perceptual discrimination of the shape of

Landolt squares was required at each attended location, which may have delayed attention shifts to a new target location. It is important to note that priority-driven attention shifts are not entirely stimulus-driven, but subject to top-down strategic control. For this reason, the speed of such shifts is unlikely to be constant, but will instead be affected by the demands of a specific selection task (see also Grubert & Eimer, 2016b, for evidence that priority-driven attention shifts operate more slowly when temporal task demands are relaxed). More generally, the finding that priority-driven shifts of attention to new target objects that are guided by target-defining stimulus features can be triggered within approximately 50 ms is important for serial models of visual search. These models have used search slopes to infer the speed of such attention shifts (e.g., Treisman & Gelade, 1980; Wolfe, 2007), and assume that priority-based attention can move between objects at rates of about 50 ms or even faster (Wolfe, 1998). The temporal pattern of N2pc components observed during priority-driven attention shifts in the current Experiment 1 and in our previous study (Grubert & Eimer, 2016b) provides electrophysiological evidence that attention can indeed move at the relatively fast speed postulated by these serial models.

In the priority-driven shift task of Experiment 2, arrow cues at the benchmark location signalled the location of the response-relevant T2 object. Here, priority-driven attention was not pulled by a particular target feature, but pushed towards a target by a feature (arrow direction) at another currently attended location. The T1/T2 N2pc onset delay measured in this task (106 ms) was longer than the delay found for colour-guided attention shifts in Experiment 1, but shorter than the delay observed during fully voluntary attention shifts. This suggests that shifts of spatial attention in response to arrow cues can be triggered about 100 ms after the onset of such cues, which is substantially faster than previous estimates based on behavioural results (e.g., Cheal & Lyon, 1991; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989). It is difficult to directly compare the time course of cued attention shifts reflected by the N2pc results of Experiment 2 with these behavioural spatial cueing studies. In these earlier studies, spatial cues were presented prior to search displays whereas cues and targets appeared simultaneously in Experiment 2. The onset of N2pc components reflects an early phase of attentional selectivity (i.e., the emergence of a spatially selective processing bias in ventral visual areas; see Eimer, 2014, 2015, for further discussion), whereas behavioural spatial cueing effects may be generated at later stages of attentional processing. The fact that colour-guided attention shifts investigated in

Experiment 1 were faster than the attention shifts elicited by spatial cues measured in Experiment 2 is interesting, because it suggests that feature signals at target locations for an attention movement are more effective in controlling the focus of attention than spatially informative signals at previously attended locations. It is possible that identifying the colour of the benchmark object in Experiment 1 was faster than discriminating the direction of the benchmark arrow in Experiment 2, and that attention shifts towards T2 could therefore be triggered earlier.[2] Priority-driven attention shifts elicited by spatial cues and shifts that are guided by target-matching features are necessarily associated with different types of sensory signals which differ in their processing demands, and this factor may be largely responsible for differences in speed between these two types of priority-driven shifts.

Because the speed of attention shifts between different objects is modulated by the amount of processing required by these objects, the N2pc onset delay between T1 and T2 objects measured in the current study will be affected by how deeply T1 had to be processed in order to determine the response-relevant T2 object. In this context, the observation that purely voluntary shifts were slower than priority-driven shifts in both experiments is particularly remarkable, because T1 processing demands were actually higher in the priority-driven tasks. When performing the voluntary tasks, localising the benchmark object was sufficient to initiate the required clockwise or anticlockwise shift of attention towards the T2 object. In the priority-driven tasks, benchmark objects not only had to be localised, but their colour or shape also had to be discriminated in order to identify T2. In spite of the fact that an additional T1 processing step was required in the priority-driven shift tasks, N2pc components to T2 targets still emerged earlier than in the voluntary tasks, demonstrating that attention shifts were triggered more rapidly. This further underlines the fact that fully voluntary movements of attention are slower than

[2] It is also conceivable that once the colour of the object at the benchmark location was detected in Experiment 1, attention was immediately shifted to the only other colour-matching item in the display (the T2 object), and that the fast shift times observed in this priority-driven task were a direct result of this colour match. However, this interpretation is not in line with the fact that very similar shift speeds were observed in our previous N2pc study of priority-driven attention shifts (Grubert & Eimer, 2016b) where the two target items in each display differed in colour.

attention shifts that are guided by visual features. When the time demands associated with T1 processing are taken into account, the true speed of priority-driven attention shifts may even be faster than suggested by the T1/T2 N2pc onset differences observed in the current study, and differences between the speed of voluntary and priority-driven shifts may even be larger.

In summary, the current study has provided new electrophysiological insights into the speed of priority-driven shifts of attention, and is the first to report on-line measures of purely voluntary movements of attention between different visual objects. We have shown that fully endogenous attention shifts that cannot be guided by visual signals are generally slower than shifts of attention that are controlled by target-matching visual features or by spatial cues. Purely voluntary attention shifts can be initiated within about 150 ms, feature-guided shifts are much faster (~50 ms), and attention shifts in response to spatial cues require about 100 ms. The speed of these three different types of attention shifts is unlikely to be completely fixed, but will vary to some degree as a function of the attentional processing demands of a particular task. The current results also demonstrate that ERP-based measures such as the N2pc component can be useful tools to uncover the temporal dynamics of attentional object selection mechanisms.

Acknowledgement

This research was supported by Grants ES/K006142/1 and ES/L016400/1 from the Economic and Social Research Council (ESRC), United Kingdom.

References

Cheal, M., & Lyon, D. (1991). Central and peripheral precuing of forced-choice discrimination. *The Quarterly Journal of Experimental Psychology*, *43*, 859-880.

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193-222.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, *87,* 272-300.

Duncan, J., & Humphreys, G. (1992). Beyond the search surface: Visual search and attentional engagement. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 578-588.

Duncan, J., Ward, R., & Shapiro, K. (1994). Direct measurement of attentional dwell time in human vision. *Nature*, *369*, 313-315.

Egeth, H., Jonides, J., & Wall, S. (1972). Parallel processing of multielement displays. *Cognitive Psychology*, *3*, 674-698.

Eimer, M. (1996). The N2pc component as an indicator of attentional selectivity. *Electroencephalography and Clinical Neurophysiology, 99,* 225-234.

Eimer, M. (2014). The neural basis of attentional control in visual search. *Trends in Cognitive Sciences, 18,* 526-535.

Eimer, M. (2015). EPS Mid-Career Award 2014: The control of attention in visual search - Cognitive and neural mechanisms. *The Quarterly Journal of Experimental Psychology*, *68,* 2437-2463.

Eimer, M., & Grubert, A. (2014). Spatial attention can be allocated rapidly and in parallel to new visual objects. *Current Biology, 24,* 193-198.

Eimer, M., Kiss, M., & Nicholas, S. (2011). What top-down task sets do for us: An ERP study on the benefits of advance preparation in visual search. *Journal of Experimental Psychology: Human Perception and Performance, 37,* 1758-1766.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39,* 175–191.

Grubert, A., & Eimer, M. (2016a). Rapid attentional selection processes operate independently and in parallel for multiple targets. *Biological Psychology*, *121*, 99-108.

Grubert, A., & Eimer, M. (2016b). The Speed of Serial Attention Shifts in Visual Search: Evidence from the N2pc Component. *Journal of Cognitive Neuroscience*, *28*, 319-332.

Grubert, A., & Eimer, M. (2015). Rapid parallel attentional target selection in single-color and multiple-color visual search. *Journal of Experimental Psychology: Human Perception and Performance, 41,* 86-101.

Hickey, C., Di Lollo, V., & McDonald, J. J. (2009). Electrophysiological indices of target and distractor processing in visual search. *Journal of Cognitive Neuroscience, 21,* 760-775.

Hickey, C., McDonald, J. J., & Theeuwes, J. (2006). Electrophysiological evidence of the capture of visual attention. *Journal of Cognitive Neuroscience, 18,* 604-613.

Hopf, J. M., Luck, S. J., Girelli, M., Hagner, T., Mangun, G. R., Scheich, H., & Heinze. H. J. (2000). Neural sources of focused attention in visual search. *Cerebral Cortex, 10,* 1233-1241.

Horowitz, T., Wolfe, J., Alvarez, G., Cohen, M., & Kuzmova, Y. (2009). The speed of free will. *The Quarterly Journal of Experimental Psychology*, *62*, 2262-2288.

Jenkins, M., Grubert, A., & Eimer, M. (2016). Rapid Parallel Attentional Selection Can Be Controlled by Shape and Alphanumerical Category. *Journal of Cognitive Neuroscience*, *28*, 1672-1687.

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: Evidence from human electrophysiology. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 1000-1014.

Miller, J., Patterson, T., & Ulrich, R. (1998). Jackknife-based method for measuring LRP onset latency differences. *Psychophysiology, 35,* 99-115.

Müller, H., & Rabbitt, P. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 315-330.

Müller, M. M., Teder-Sälejärvi, W., & Hillyard, S. A. (1998). The time course of cortical facilitation during cued shifts of spatial attention. *Nature Neuroscience*, *1*, 631-634.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, *29*, 1631-1647.

Posner, M. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3-25.

Posner, M., Snyder, C., & Davidson, B. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *109*, 160-174.

Townsend, J. (1990). Serial vs. Parallel processing: Sometimes they look like Tweedledum and Tweedledee but they can (and should) be distinguished. *Psychological Science*, *1*, 46-54.

Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12,* 97–136.

Ulrich, R., & Miller, J. O. (2001). Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. *Psychophysiology, 38,* 816–827.

Ward, R., Duncan, J., & Shapiro, K. (1996). The Slow Time-Course of Visual Attention. *Cognitive Psychology*, *30*, 79-109.

Wolfe, J. M. (1998). Visual memory: What do you know about what you saw? *Current Biology*, *8*, 303-304.

Wolfe, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin and Review, 1,* 202-238.

Wolfe, J. M. (2007). Guided Search 4.0: Current progress with a model of visual search. In W. Gray (Ed.), *Integrated Models of Cognitive Systems* (pp. 99-119). New York: Oxford.

Wolfe, J. M., Alvarez, G., & Horowitz, T. (2000). Attention is fast but volition is slow. Nature, *406*, 691.

Woodman, G., & Luck, S. (2003). Serial deployment of attention during visual search. *Journal of Experimental Psychology: Human Perception & Performance*, *29*, 121-138.

Woodman, G. F., & Luck, S. J. (1999). Electrophysiological measurement of rapid shifts of attention during visual search. *Nature, 400*, 867-869.

Figure Legends

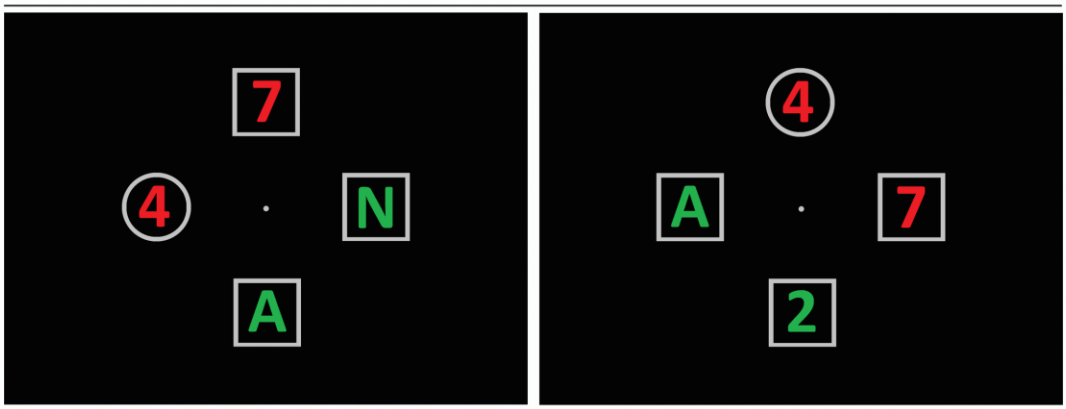
Figure 1. Schematic illustration of the search displays in Experiments 1 and 2. Displays with T1 or T2 objects on the horizontal midline are shown in the left and right panels, respectively. In Experiment 1 (top panels), T1 benchmark objects were defined by their unique shape (e.g., the circle among squares). In the priority-driven shift task, T2 was defined as the object that matched the colour of the item at the benchmark location (the red "7" in Figure 1). In the voluntary shift task, T2 was defined as the object at the position clockwise or anticlockwise from T1. Search displays were identical in both tasks. In the priority-driven shift task of Experiment 2 (middle panels), T1 was defined by its colour and T2 was signalled by the direction of the arrow shape at the benchmark location (e.g., the "K" indicated by red benchmark arrows in Figure 1). In the voluntary shift task of Experiment 2 (bottom panels), T1 was again defined by its colour, and T2 by its location relative to T1 (clockwise or anticlockwise). In all tasks, participants reported whether T2 was a letter or a digit. See the online article for the colour version of this figure.

Figure 2. N2pc results in the priority-driven and voluntary shift tasks of Experiment 1. The left and middle panels show grand-average ERP waveforms measured in the 500 ms interval after search display onset at posterior electrodes PO7/PO8 contralateral and ipsilateral to a horizontal T1 or T2 object. ERPs are shown separately for displays where T1 appeared on the horizontal midline and displays where T2 was presented horizontally. The right panels show N2pc difference waveforms obtained by subtracting ipsilateral from contralateral ERPs, separately for horizontal T1 and horizontal T2 trials and both shift tasks. Circles mark the point in time when N2pc difference waves reached an absolute onset criterion value of -0.5 μV, and shaded areas indicate N2pc time windows.

Figure 3. N2pc results in the priority-driven and voluntary shift tasks of Experiment 2. Grand-average ERP waveforms measured in the 500 ms interval after display onset at

electrodes PO7/PO8 contralateral and ipsilateral to T1/T2 and the corresponding ipsilateral-contralateral N2pc difference waveforms are shown separately for displays with horizontal T1 and horizontal T2 objects. Circles mark the point in time when N2pc difference waves reached an absolute onset criterion value of -0.5 μV, and shaded areas indicate N2pc time windows.

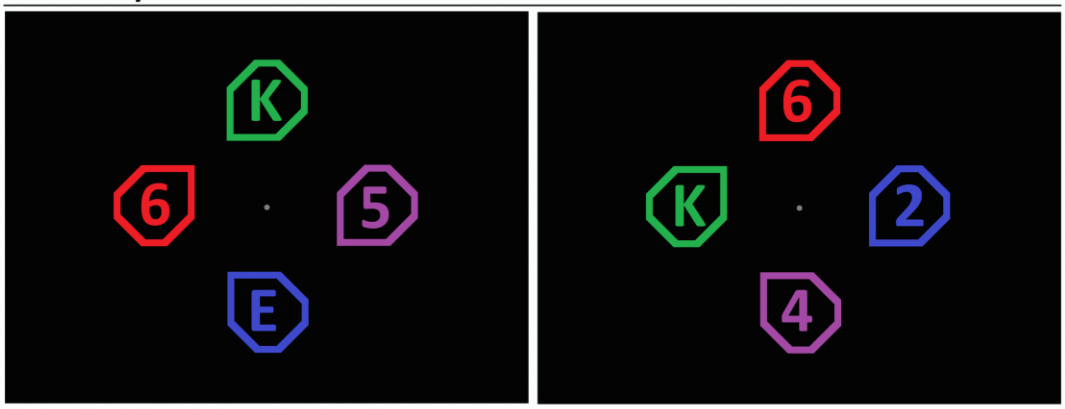
Experiment 1



Horizontal T1 display *Horizontal T2 display*

Experiment 2

Priority-driven shift task



Voluntary shift task

Horizontal T1 display *Horizontal T2 display*

Figure 1

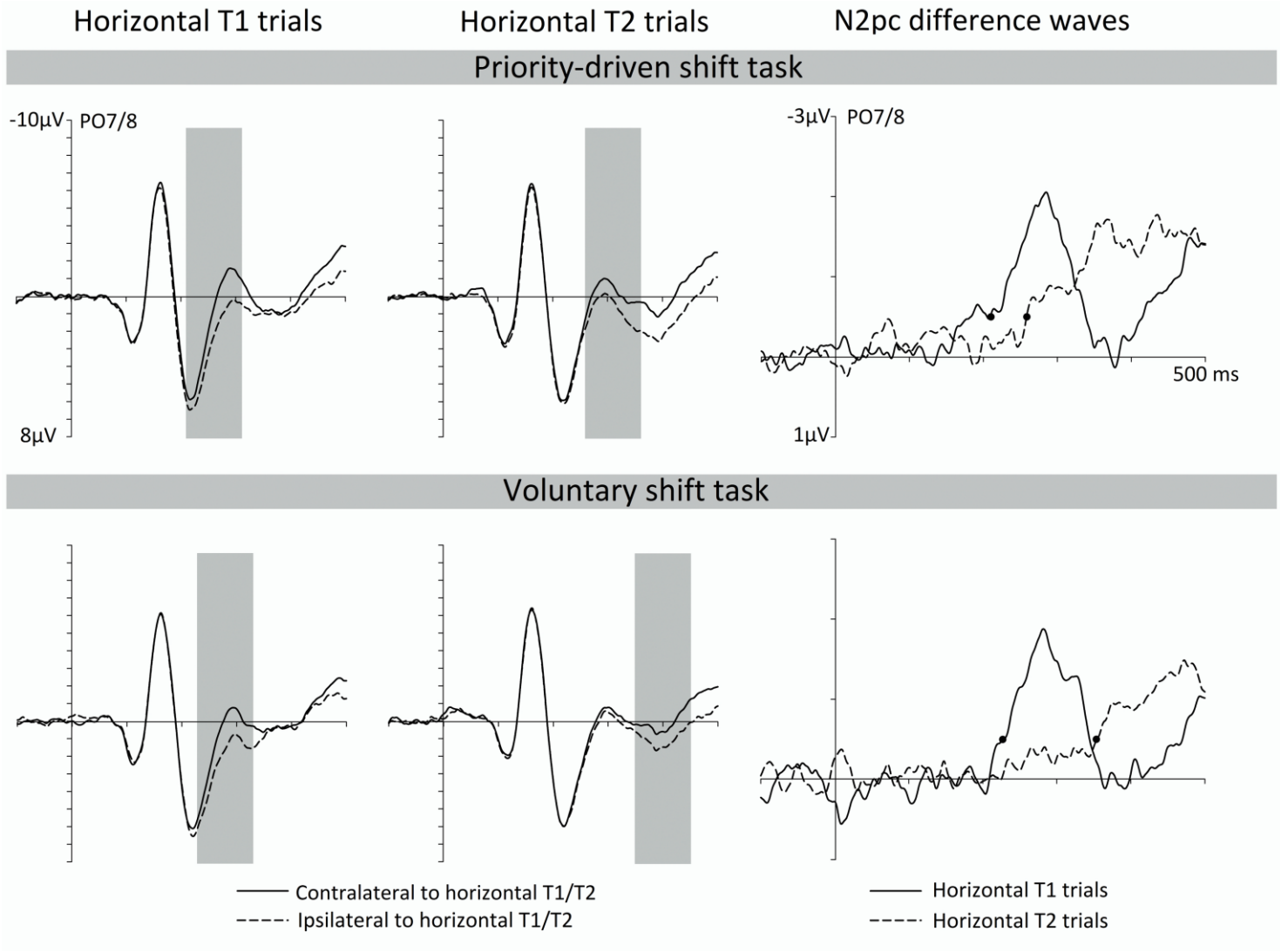

Horizontal T1 trials
Horizontal T2 trials
N2pc difference waves
Priority-driven shift task
-10µV
PO7/8
8µV
-3µV
PO7/8
500 ms
1µV
Voluntary shift task
Contralateral to horizontal T1/T2
Ipsilateral to horizontal T1/T2
Horizontal T1 trials
Horizontal T2 trials

Figure 2

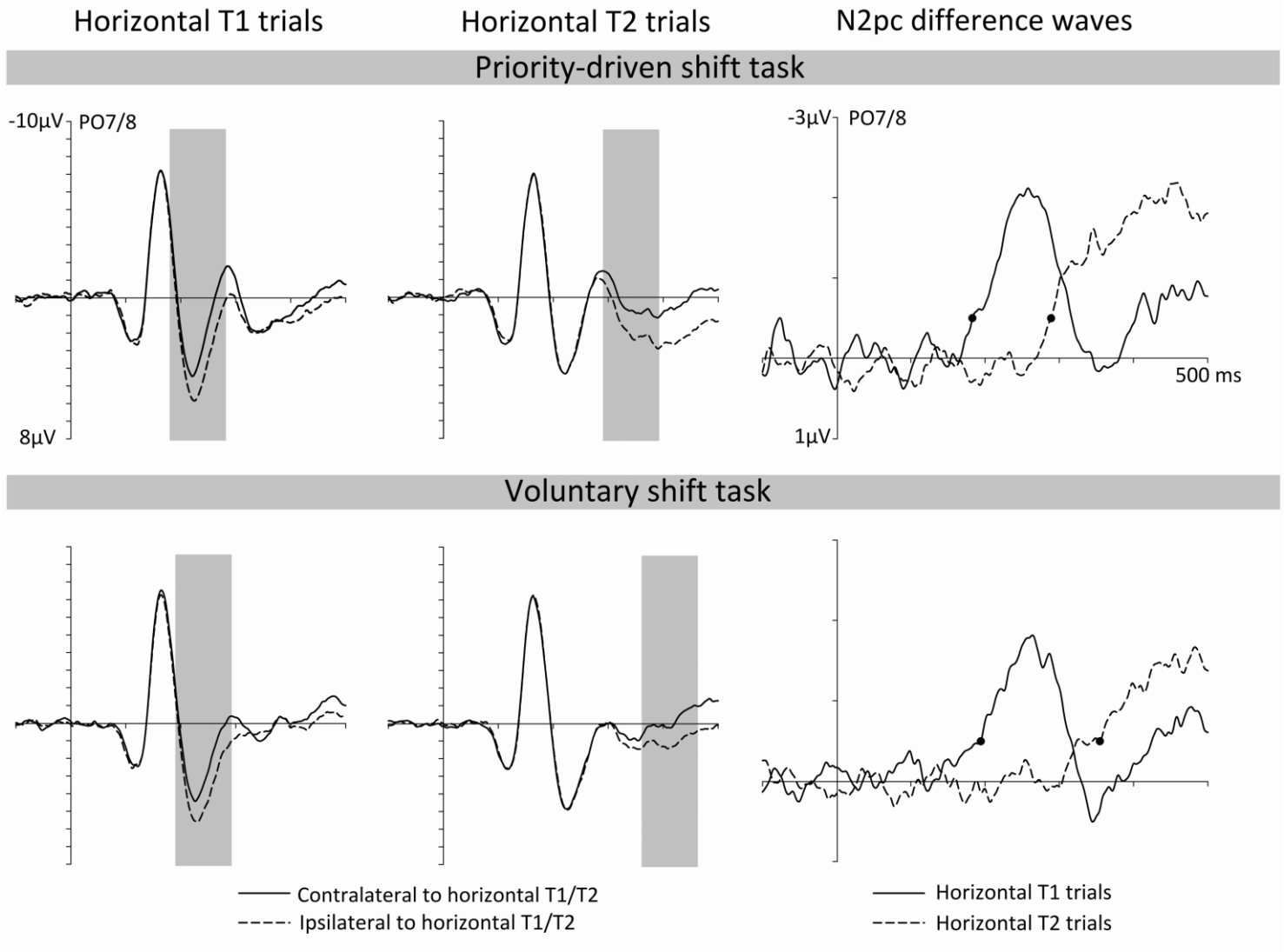

Horizontal T1 trials
Horizontal T2 trials
N2pc difference waves
Priority-driven shift task
-10µV
PO7/8
8µV
-3µV
PO7/8
500 ms
1µV
Voluntary shift task
Contralateral to horizontal T1/T2
Ipsilateral to horizontal T1/T2
Horizontal T1 trials
Horizontal T2 trials

Figure 3